

WADC TECHNICAL REPORT 52-287

4049

54-22739

FILED COPY

**SURVEY, CHARACTERISTICS, AND EVALUATION OF  
HIGH-PERFORMANCE MAGNETIC CORE MATERIALS**

**SIEGFRIED R. HOH**  
**COMPONENTS AND SYSTEMS LABORATORY**

NOVEMBER 1952

Statement A  
Approved for Public Release

**WRIGHT AIR DEVELOPMENT CENTER**

**PLEASE RETURN THIS COPY TO:**

**ARMED SERVICES TECHNICAL INFORMATION AG  
DOCUMENT SERVICE CENTER  
Knott Building, Dayton 2, Ohio**

*Because of our limited supply you are requested to return  
this copy as soon as it has served your purposes so that  
it may be made available to others for reference use.  
Your cooperation will be appreciated.*

20030103201

## NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The information furnished herewith is made available for study upon the understanding that the Government's proprietary interests in and relating thereto shall not be impaired. It is desired that the Judge Advocate (WCJ), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, be promptly notified of any apparent conflict between the Government's proprietary interests and those of others.



**SURVEY, CHARACTERISTICS, AND EVALUATION OF  
HIGH-PERFORMANCE MAGNETIC CORE MATERIALS**

*Siegfried R. Hob*  
*Components and Systems Laboratory*

*November 1952*

*RDO No. 112-157*

Wright Air Development Center  
Air Research and Development Command  
United States Air Force  
Wright-Patterson Air Force Base, Ohio

McGregor & Werner, Dayton, Ohio  
200, March, 1953

## FOREWORD

This report was initiated by the Components and Systems Laboratory of the Directorate of Laboratories at Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The report was prepared as part of the work essential to RDO No. 112-157, "Magnelectric Materials." The author of the report was the project engineer.

A major portion of the information contained herein was first presented by the author as a technical paper at The National Conference on Airborne Electronics, 12 May through 14 May 1952. The manuscript of this report was presented on 16 June 1952 for publication as a Wright Air Development Center Technical Report.

Acknowledgment is made of the cooperation of the following companies and organizations in supplying information: Allegheny-Ludlum Steel Corporation of Brackenridge, Pennsylvania; Armco Steel Corporation of Middletown, Ohio; Arnold Engineering Company, Marengo, Illinois; Bell Telephone Laboratories, Murray Hill, New Jersey; D. M. Steward Manufacturing Company, Chattanooga, Tennessee; Ferroxcube Corporation of America, Saugerties, New York; General Ceramics and Steatite Corporation, Keasby, New Jersey; Stackpole Carbon Company, St. Marys, Pennsylvania; and Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.

Particular appreciation for special communications is extended to Messrs. G. H. Cole, D. C. Dieterly, and M. F. Littman of the Armco Research Laboratories and to Mr. W. Stifler of the Ferroxcube Corporation of America.

## ABSTRACT

The great number of high performance magnetic core materials is surveyed and various direct current and alternating current characteristics of such materials are presented in table and chart formats. Figures of merit are derived and their suitability for a characterization of materials is discussed. These figures of merit are used to compare and evaluate such different types of core materials as laminated materials, powdered materials, and ferrites.

Universal charts covering characteristics of high performance core materials over wide frequency and flux density ranges are presented herein. A portion of this report is devoted to the review and consolidation of various permeability concepts which are used to describe material characteristics at high frequencies.

## PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange of ideas.

FOR THE COMMANDING GENERAL:

*for* C. C. Eckert  
RICHARD S. CARTER  
Colonel, USAF  
Chief, Components and  
Systems Laboratory  
Directorate of Laboratories

## TABLE OF CONTENTS

Introduction . . . . .	<u>Page</u> 1
Direct Current Characteristics of Magnetic Materials . . . . .	1
Alternating Current Characterization and Evaluation . . . . .	10
Summary . . . . .	28
Index of Symbols . . . . .	29
Bibliography. . . . .	30

# LIST OF ILLUSTRATIONS

<u>Figure No.</u>		<u>Page</u>
1	Half DC Hysteresis Loops of Various Core Materials	6
2	Core Loss (In-phase Volt-amperes Per Pound)	11
3	Exciting Volt-amperes	13
4	Exciting Volt-amperes Plus In-phase Volt-amperes Per Pound	15
5	Exciting Volt-ampere Vector Locus Resulting in Equal Figure of Merit for Given Flux Density and Frequency	17
6	Core Loss at Low Flux Density	19
7	AC Characteristics at Low Flux Density	22
8	Apparent Permeability at Low Flux Density	23
9	Loci of Complex Permeability Vectors With Equal Figure of Merit $\frac{\mu_r}{\mu^2}$	28

## TABLES

<u>Table No.</u>		<u>Page</u>
I	DC Data on Metallic Core Materials	2, 3, 4
II	Ferrite Characteristics -- Data Refer to DC Unless Stated Otherwise	8, 9
III	Permeability Definitions Pertinent to Cyclic or Alternating Magnetization	24

## INTRODUCTION

The comparison and evaluation of magnetic core materials present problems because of the wide variety of both materials and characteristics. This is particularly true in the field above power frequencies where different kinds of materials such as thin laminations, powdered irons, and non-metallic ferrites are competing. Except for early compilations of data on direct current (dc) characteristics (see references 1, 6, and 11), the available information on magnetic materials, which would aid in selection, is scattered throughout numerous publications and frequently does not lend itself to the making of comparisons and evaluations.

The purpose of this report is to present a brief survey of magnetic materials and to derive and present characteristics in a form which is suitable for comparison and evaluation. Data are compiled from various publications and from manufacturers' information. (See references.)

No attempt has been made to cover as many materials as are available. Emphasis has been placed on presenting data on high performance magnetic materials which are commercially obtainable in the United States. A few experimental and foreign materials which exhibit interesting or outstanding characteristics have been included.

Designers who are not too familiar with magnetic materials are cautioned about the wide variations which may be encountered in the characteristics of magnetic materials. All figures presented herein are to be understood as approximate. Deviations between material samples can exceed 100%, particularly in such characteristics as permeability, coercive force, and others.

## DIRECT CURRENT CHARACTERISTICS OF MAGNETIC MATERIALS

The large number of metallic core materials is arranged according to composition in Table I. This arrangement automatically shows identical or similar materials even though they may have entirely different trade names.

Since iron is the most important component of magnetic alloys, the dc characteristics of a pure iron sample are presented as the first item in Table I. Iron, if carefully purified and prepared, has very good magnetic properties. However, a shortcoming of pure iron is its low resistivity which is detrimental in all alternating current (ac) applications. The resistivity of pure iron can be increased by the addition of small quantities of silicon.



METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCIVE F. [OERST.]	RESISTIVITY [MICROHM CM]	CURIE TEMP. [°C]
					INITIAL	MAXIM.					
	Purified Iron		0.02 Imp.	Low Resist.	25,000	275,000	21.5	13.6	0.05	10	770
SILICON-IRON	Silicon-Iron	see ref. 4	4 Si	Transformer	400	7,000	20	12	0.5	60	690
	Hypersil	Westinghouse		Grain					0.1		
	Trancor 3X	Armco	3.5 Si	Oriented	1,500	35,000	20	13.7	0.3	50	750
	Silectron	Allegheny-Ludlum									
	Sendust	Japanese	9.5 Si 5.5 Al	HF Powder	30,000	120,000	10	5	0.05	80	
COBALT-IRON	Hyperco	Westinghouse	35 Co 0.5 Cr	High	650	10,000	24	13	1	28	970
	2V Permendur	Western Electric	49 Co 2V	Saturation	800	4,500		14	2	25	980
NICKEL-IRON	45-25 Perminvar	Bell Telephone Laboratories	45 Ni 25 Co	"Constant"	400	2,000	15.5	3.3	1.2	20	715
	7-70 Perminvar		70 Ni 7 Co	Permeability	850	4,000	12.5	2.4	0.6	15	650
	Conpernik	Westinghouse	50 Ni		1,500	2,000	16			45	
	36 Isoperm	German	36 Ni 9 Cu	High	60	65				70	300
	50 Isoperm		50 Ni	Frequency	90	100	16			40	500

METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCIVE F. [OERST.]	RESISTIVITY [MICROHM CM]	CURIE TEMP. [°C.]
					INITIAL	MAXIM.					
NICKEL-IRON	45 Permalloy	Western Electric	45 Ni	Combine	2,700	23,000	16.5	8	0.3	45	440
	"4750"	Allegheny-Ludlum	47 - 50 Ni		9,000	50,000	16	6.2*	0.08*	52	430
	Armco 48	Armco	48 Ni	Good							
	Nicaloi	General Electric	49 Ni	Permeab.							
	High Perm 49	Carpenter	49 Ni	and	5,000	50,000	15	6.5	0.03	43	475
	Hipernik	Westinghouse	50 Ni, Si, Mn	Flux D.	4,000	100,000		8*	0.03*	45	500
	Monimax	Allegheny-Ludlum	47 Ni 3 Mo	High	2,000	38,000	15		0.06	80	390
	Sinimax	Ludlum	42 Ni 3 Si	Resist.	3,500	30,000	11		0.1	90	290
	Permenorm 5000Z	German	45 to 50 Ni	Rect. Hyst. Loop	400	40,000	15.5	13	0.2	40	450
	Permenite	I.T.E. Circ. Br. Co.									
	Deltamax	Arnold Engr. Co.			1,700	100,000	16	15	0.4	50	500
	Hypernik V	Westinghouse									
	Orthonik	Armco	65 - 68 Ni		1,500	250,000 600,000	13	13	0.03	20	600
	Orthonol	Navy Ordn Lab.									
	65 Permalloy	Bell Tel. Lab.									

\*B<sub>max</sub> = 10,000 Gauss

TABLE I (continued)

METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCITIVE F. [OERST.]	RESISTIVITY [MICROHM CM]	CURIE TEMP. [°C]
					INITIAL	MAXIM.					
NICKEL-IRON	1040 Alloy	German	72 Ni 14 Cu 3 Mo	Highest	40,000	100,000	6	2.5	0.02	55	290
	Mumetal	Allegheny-Ludlum	77 Ni 5 Cu 2 Cr		20,000		8	6	0.05	60	400
	78 Permalloy	Western Electric	78 Ni 0.6 Mn	Perm.	9,000	75,000	10.7	6	0.05	16	580
	4-79 Mo-Permalloy	Arnold Engr. Co.	79 Ni 4 Mo		20,000		8	5.5	0.05	55	
	Supermalloy		79 Ni 5 Mo	Low	55,000	500,000	6.8		0.002	65	400
	Hymu 80	Carpenter	80 Ni	Sat.	±150,000	±10 <sup>6</sup>	±7.8		±0.05		
					10,000	100,000	8		0.06	58	460

Silicon-iron was the first special alloy developed specifically for use as a magnetic core material. Because of its relatively low cost and its satisfactory performance in a wide field of applications, silicon-iron has dominated the field in the electrical industry.

There are more than ten manufacturers producing more than one hundred brands of magnetic silicon-irons in the United States, alone (Ref. 15). Many of these brands are identical in silicon content and performance. This class of material, which ranges in silicon content from less than .25% up to approximately 5%, is not covered in detail in this report. The differences in performances are small in comparison with the differences encountered in this survey. Data on a 4% silicon transformer iron are given in Table I as an example and as an aid in making comparisons.

Single crystals of magnetic materials are, generally, anisotropic. This means that the characteristics depend upon crystal orientation. Single crystals of magnetic materials have not yet been used beyond the laboratory, but grain-orientated materials, which have a preferred orientation of the crystals in a suitable direction, already play an important role in commercial materials. Proper grain-orientation results in a more rectangular hysteresis loop and in a higher operating flux density. Half hysteresis loops of various materials, including those with grain-orientation, are compared in figure 1.

Cobalt and nickel, the other two important ferromagnetic elements, have no significance as magnetic materials in pure form; however, they are the most important alloying elements. The addition of cobalt to iron substantially increases the saturation of iron, as in the case of Permendur and Hyperco. The advantage of higher saturation of these materials is partly overcome by higher losses. Reductions in size and weight can be obtained only in some power applications. Furthermore, cobalt is a "critical" material.

Other alloys, designated by the trade name, Perminvar, (Ref. 9) have a smaller cobalt content than does Permendur and Hyperco and also display unique magnetization curves. The Perminvar alloys have constant permeability and almost no hysteresis up to flux densities of 1,000 Gauss. Even at still higher flux densities, residual magnetization and coercive force remain practically zero. The permeability of Perminvar, however, remains constant only as long as high magnetization is avoided. Other materials which have constant permeability are Conpernik, Isoperm, and powdered irons.

Nickel is of great significance as an alloying component in high performance core materials. Iron-nickel alloys are characterized by high permeability if properly processed. The saturation flux density, however, is reduced by nickel. Commercial iron-nickel alloys can, for the purposes of this report, be divided into two groups. This rough division groups together those alloys which contain 45% to 50% nickel and places in the other group those alloys which have a nickel content of from 65% to 80%.

The 45-50% nickel alloys display a higher saturation and generally a higher resistivity than do the alloys with higher nickel content. Small quantities of other alloying elements and special processing can produce desirable variations in characteristics. Examples in this group are Sinimax in which the resistivity has been increased to 90 microhm/cm and Isoperm from which low ac distortion and low high-frequency losses have been obtained. Alloys in the 45-50% nickel group

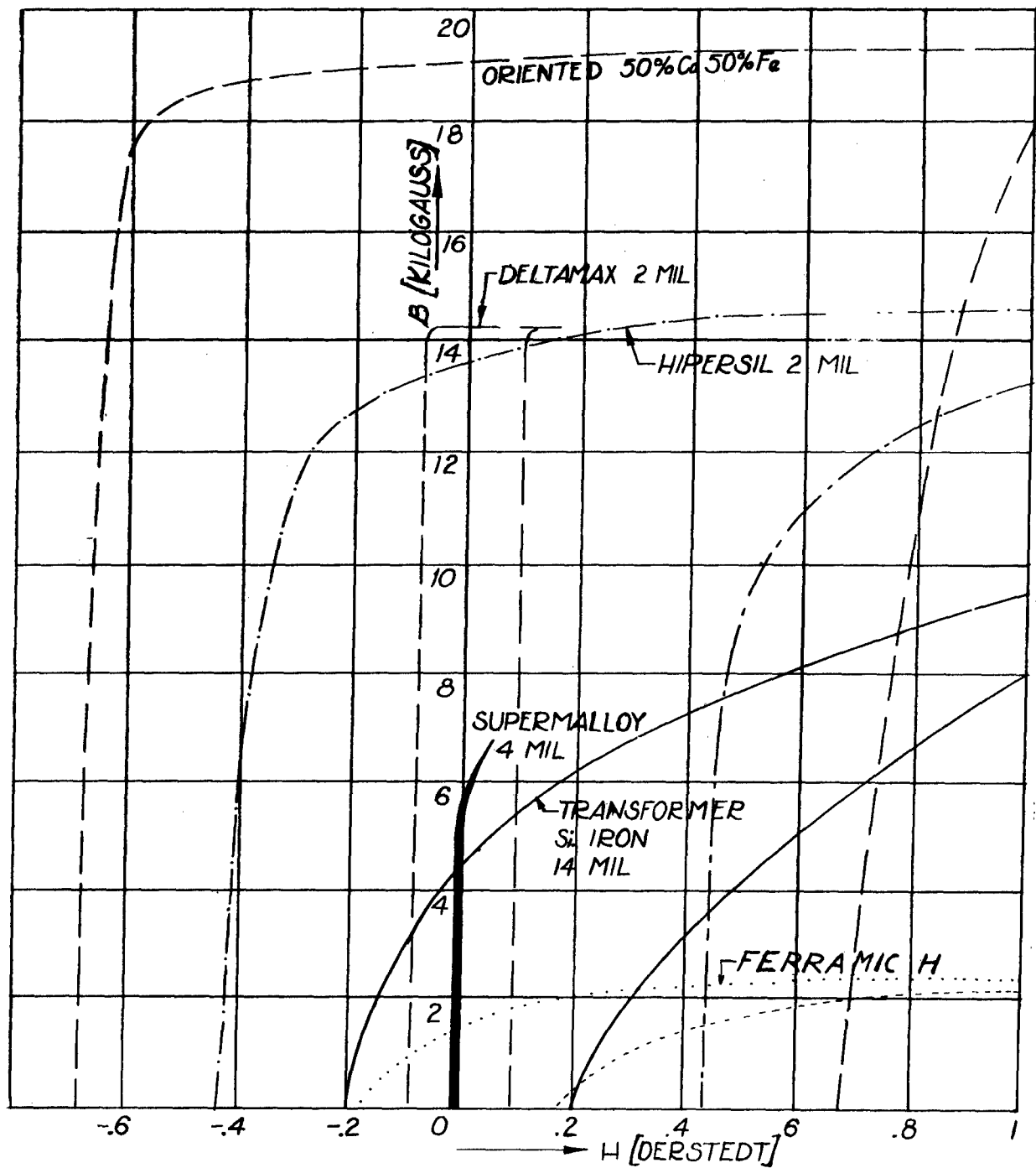


Fig. 1 Half DC Hysteresis Loops of Various Core Materials

have a great significance in the grain-orientated form in which they display rectangular hysteresis loops (see Deltamax: Fig. 1 and Ref. 7) which are desirable in magnetic amplifiers, magnetic pulse generators, computers, mechanical rectifiers, harmonic generators, etc.

As compared to the 45-50% group, the materials with higher nickel content have higher permeabilities, lower coercive forces, but much lower saturation. Unique characteristics of the alloys in this group are low magnetostriction and low anisotropy. Superalloy (Ref. 4) is the latest development in this group and can be rated as the most advanced among the iron-nickel alloys. The hysteresis loop of Superalloy condenses into one line if plotted for comparison with other materials. (See figure 1.)

The interesting characteristics of 65% Permalloy are obtained by an anneal in a magnetic field which has an effect on the hysteresis loop similar to that which results from grain-orientation. With magnetically annealed 65% Permalloy, almost perfectly rectangular hysteresis loops have been obtained. (See Ref. 8.)

The ferromagnetic ferrites, listed in Table II, represent a different class of materials. Their fundamental differences, as compared to the materials which have been discussed so far, are their non-metallic properties such as high resistivity and low weight. Ferrites are ceramic materials composed of certain divalent metal oxides among which is  $\text{Fe}_2\text{O}_3$ . Unfortunately, the term "ferrite" also denotes a particular ( $\infty$ ) crystal phase of pure iron with which the ferrites under discussion herein should not be confused. Though known for a long time (German patents in 1909), practical ferrites did not become available until after World War II.

Low saturation and low permeability of ferrites exclude them from most low frequency applications but their high resistivity makes them superior at medium and high frequencies as is shown in the section entitled, "Alternating Current Characterization and Evaluation." The Curie temperatures of ferrites are, generally, lower than those of metallic materials. At present, high permeability can only be obtained at low Curie temperatures. Maximum permeabilities up to 9,000 coupled with Curie temperatures of approximately  $80^\circ\text{C}$  have been reported. Manufacturers can supply far more ferrite materials with desired combinations of characteristics than are listed in this report. Also, compounds with highly rectangular hysteresis loops have been announced. For more information on ferrites see references 3, 5, 17, 18, and 19.

TRADE NAME	COMPANY	RECOMMENDED FREQUENCY RANGE OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL INDUCTION [K GAUSS]	COERCIVE FORCE [OERSTED]	RESISTIVITY [OHM CM]	CURIE TEMP. [°C]	TEMP. COEFF. OF IN. PERM. [% PER °C]
			INITIAL	MAXIM.						
Ceramag 5N 7 8  (all data referring to 60 cps)	Stackpole Carbon Co., St. Marys, Pa.	see graph	560	1,840	2,300	1,400	0.4	10 <sup>3</sup>	170°	
			540	4,600	2,460	1,750	0.2	1.8 x 10 <sup>4</sup>	170°	
			450	1,700	2,850	2,100	0.6	2.1 x 10 <sup>4</sup>	190°	
Ferramic A B C D E G H I J	General Ceramics and Steatite Corp., Keasbey, N. J.	see graphs  Const. Perm.	15	97	0.84	0.61	3.7	10 <sup>9</sup>	280	0.65
			95	183	1.9	0.83	3	2 x 10 <sup>5</sup>	260	0.04
			220	710	3.8	2.7	2.1	2 x 10 <sup>3</sup>	330	0.4
			410	1,030	3.1	1.3	1	3 x 10 <sup>7</sup>	165	0.3
			750	1,710	3.8	1.9	0.65	4 x 10 <sup>5</sup>	160	0.25
			410	3,300	3.2	1	0.25	1.5 x 10 <sup>8</sup>	160	1.3
			850	4,300	3.4	1.4	0.18	10 <sup>5</sup>	150	0.66
			900	1,000	1.5	0.6	0.4	2 x 10 <sup>5</sup>	70	0.3
			330	750	2.9	1.6	0.8		180	0.22
			at 1 megacycle							
Ferroxcube 3 3C For more com- pounds see figure 7	Ferroxcube Corp. of Am., 50 E. 41st St. New York, N. Y.		1,000	1,200	3		0.2	10 <sup>3</sup>	140	
			900	1,100	3.5				160	

TABLE II Ferrite Characteristics -- Data Refer to DC Unless Stated Otherwise

TRADE NAME	COMPANY	RECOMMENDED FREQUENCY RANGE OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL INDUCTION [K GAUSS]	COERCIVE FORCE [OERSTEDT]	RESISTIVITY [OHM CM]	CURIE TEMP. [°C]	TEMP. COEFF. OF IN. PERM. [% PER °C]
			INITIAL	MAXIM.						
Lavite FIS	D. M.		1,000	3,000					250	
FX-6S	Steward	20-200 MC	8-11	100	0.6	0.5	3.7	10 <sup>6</sup>	200	0.03
FX-22S	Manuf. Co.	1-20 MC	15-20	120	0.9	0.6	3.7	10 <sup>6</sup>	200	0.03
FX-15S	Chattanooga	High Sat.) to	250	3,000	5	1.9	1	10 <sup>6</sup>	200	0.45
FX-27S	Tenn.	Transf. } 150 KC	850	4,000	3.5	1.5	0.25	10 <sup>6</sup>	150	0.5
FX-18S		Ant. Rod 1 MC	300	750	3	1.6	0.8	10 <sup>7</sup>	200	<3.5
High Perm.		1-150 KC	1,000	5,000	4	1.5	0.15	10 <sup>6</sup>	150	0.1

TABLE II (continued)



## ALTERNATING CURRENT CHARACTERIZATION AND EVALUATION

Since core materials are generally used in alternating fields, their ac characteristics are more conclusive for evaluation purposes than are the dc characteristics. Alternating current characteristics, particularly, have to incorporate the losses which occur in a material. Core losses of various materials, in watts per pound, are presented in figure 2 with flux density as the ordinate. Frequencies, materials, and lamination thicknesses appear as parameters. It should be noted that in this representation, in which losses are given in watts per pound, ferrites are penalized because of their lower specific gravity. A comparison based on the losses per unit volume would make the advantages of ferrite materials at high frequencies more apparent. Even in the comparison on a watts per pound basis shown in figure 2, Ferroxcube III B appears clearly superior at 100 kilocycles. This advantage is particularly great at low flux densities.

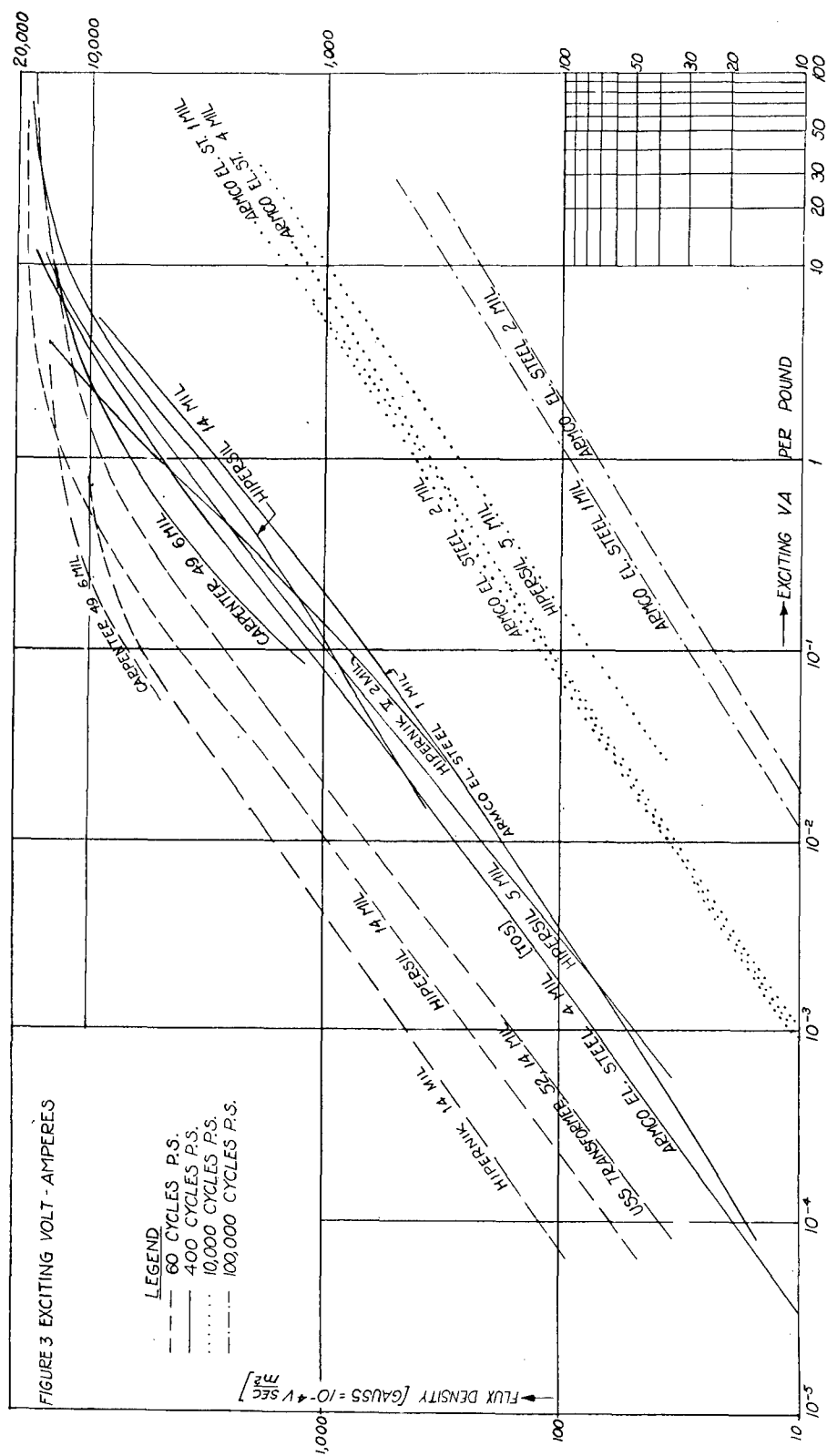
Loss figures, alone, do not characterize a material and cannot be used for general evaluation. They have to be supplemented by other data such as exciting volt-amperes per pound. These characteristics are plotted in figure 3 which corresponds in representation with figure 2.

A suitable combination of both the losses expressed in watts per pound and the apparent watts expressed in exciting volt-amperes per pound can provide a figure of merit which may be used for the evaluation of materials. It should be noted that the smallest possible losses and exciting volt-amperes are desired for a given flux density. Hence, a single figure of merit can be derived by adding the losses of in-phase volt-amperes and the exciting volt-amperes. Such data are plotted in figure 4 which corresponds to figures 2 and 3 in representation. Materials with the lowest volt-ampere figures for a given frequency and flux density have to be rated highest in this diagram.

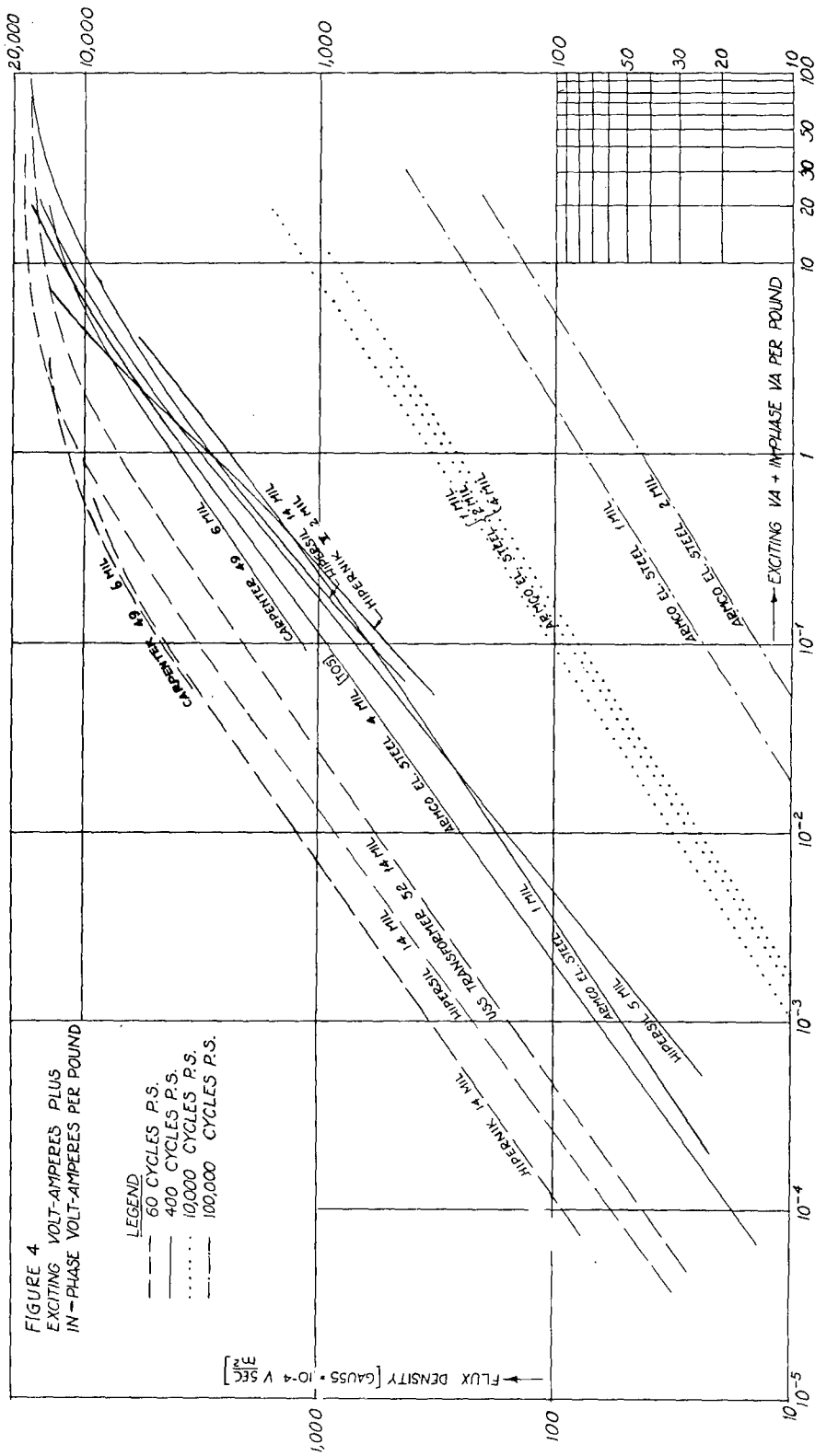
It must be emphasized that no particular physical meaning is attributed to the figure of merit thus derived. For simplification, volt-ampere vectors ("Phasors") are arbitrarily added as scalars. It should be realized that a figure of merit is, in general, more or less arbitrary and that its limitations should be studied in order to avoid misleading results. The meaning and possible limitation of the figure of merit, as proposed in the previous paragraph, can be understood better by noting the presentation in figure 5 where the locus is depicted for all exciting volt-ampere vectors for which the figure of merit is equal. This locus represents the exciting volt-amperes of all materials which would have to be rated as equal. The intersection of the locus with the reactive axis represents a material without any loss but with a rather low permeability. These conditions can be approximated with powdered core materials. The intersection of the locus with the in-phase axis represents a material with rather high losses but with a permeability of infinity because no magnetizing current is required to give rise to a certain assumed flux density. This type of material can be approximated by a perfectly cut single crystal of pure iron.



**Blank Pages**



**Blank Pages**



**Blank Pages**

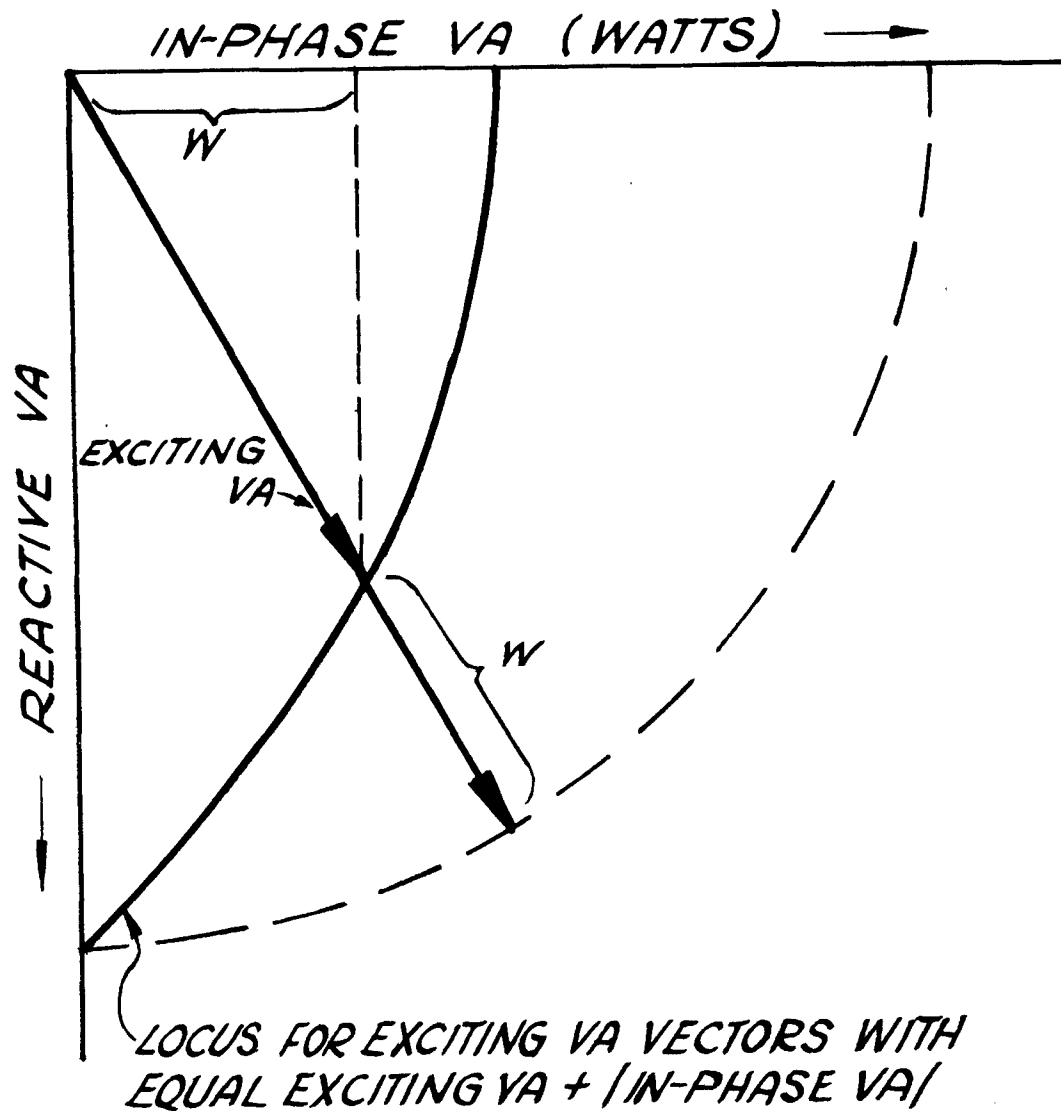


Fig. 5 Exciting Volt-ampere Vector Locus Resulting in Equal Figure of Merit for Given Flux Density and Frequency



Characteristics of those materials which have extremely small or great phase angles are not available and hence could not be incorporated in figure 4. Even sufficient data on ferrites are not yet available. The materials which are represented in figure 4 differ only slightly in characteristics and the figures of merit plotted there should provide a suitable base for evaluation of laminated core materials.

At very low flux densities, such characteristics as are presented in figures 2 through 4 are not very practical. Instead of exciting volt-amperes and power losses, reactive and resistive components of impedance are used to characterize inductors and core materials. Expressing the total loss component of an inductor by an equivalent series resistance  $R_s$ , the loss tangent  $\tan \delta = \frac{R_s}{\omega L_s}$

relates the resistive component  $R_s$  to the reactive component  $\omega L_s$ . The expression for  $\tan \delta$  is also denoted as "dissipation factor" D or the reciprocal of the "quality" or "storage" factor Q. At high Q values, the power factor

$\cos \varphi = \frac{1}{\sqrt{Q^2 + 1}}$  becomes equal to the dissipation factor, hence, it can be written

$$\tan \delta = \frac{R_s}{\omega L_s} = D = \frac{1}{Q} \longrightarrow \cos \varphi \quad (1)$$

The total series resistance  $R_s$  is composed of a component  $R_c$  which represents the effective series resistance originating in the coil and of a component  $R_m$  which represents an effective series resistance that is caused by the losses in the magnetic core. This can be written

$$R_s = R_c + R_m$$

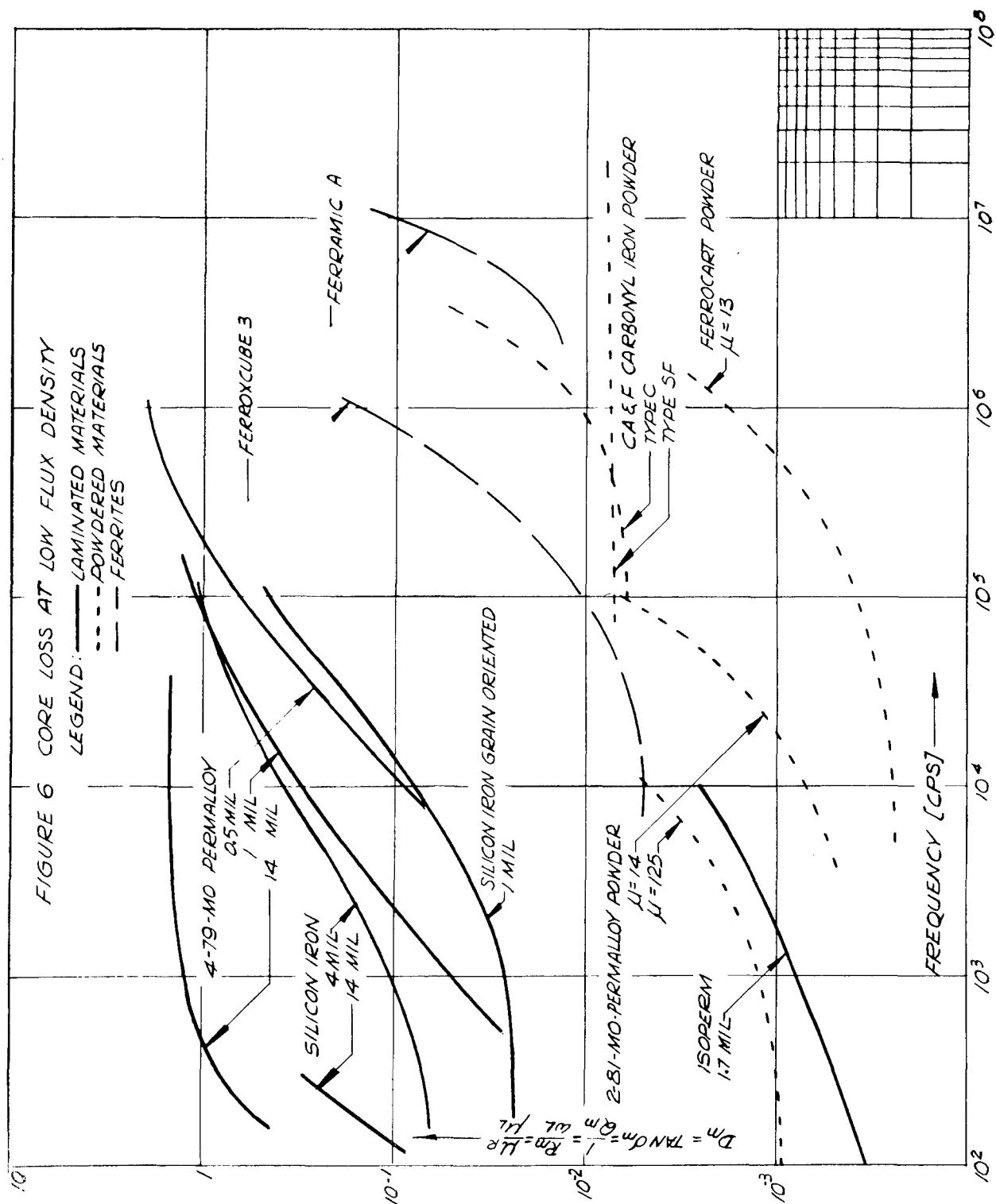
$$\frac{R_s}{\omega L_s} = \frac{R_c}{\omega L_s} + \frac{R_m}{\omega L_s} \quad (2)$$

It has been shown by various authors that the loss tangent of a ring core is independent of core dimensions and even independent of the inductance L. (For example see reference 12.) For this reason, the loss tangent  $\frac{R_m}{\omega L_s}$  which is

derived from a closed ring core becomes a practical factor for characterizing material losses.

The loss tangent or its equivalent factors have been depicted in figure 6 for different materials. Several of these curves, particularly those for powdered materials, were computed from loss coefficients (Ref. 12, 13). In these cases, a flux density of 10 Gauss was assumed. Some publications state that the flux densities were very low and the hysteresis losses negligible. It can be assumed that the flux densities involved in figures 6, 7, and 8 are 10 Gauss or less, except the permeability of Supermalloy which is given for  $B_m = 20$  Gauss. At these low flux densities, the hysteresis losses are actually only a small part of the total losses and small differences in flux density do not affect loss data substantially.

Eddy current losses play a more important role. Such losses prevail in metallic materials at higher frequencies because the losses are proportional to the second power of frequency. Eddy current losses are also proportional to the



second power of material thickness. This illustrates the importance of subdividing a metallic material into thin laminations or powdered particles. The reduction of losses by the subdivision of the material can be noted in all characteristics. For example, see data on 4-79-Mo Permalloy (Fig. 6) with the lamination thickness being 0.5, 1, and 14 mil. (1 mil. = 0.001 inch).

A further reduction of total losses by finer subdivisions of metallic materials is limited. Coercive forces, in particular, will increase as the material thickness is further decreased. Extremely thin laminations cannot be stamped and stacked but have to be wound into toroidal cores. The thickest laminations presently produced are about 0.15 mil. Further substantial reductions cannot be expected because of the difficulties in rolling the materials and because of the decrease in magnetic qualities such as an increase in coercive force. High-frequency applications of thin laminated materials are pulse transformers, magnetic pulse generators, digital computers, and others.

There appears to be a distinct difference in losses (see Fig. 6) by a factor of more than 10 between the laminated materials and the good powdered and ferrite materials. An exception is Isoperm, a German loading coil material which is unique in the field of laminated materials insofar as the dissipation factor is concerned. In Isoperm, losses have been reduced down to those of the best powdered materials. The permeability of Isoperm is, however, substantially lower than that of other laminated materials. High permeability materials such as laminated Mo-Permalloy have the highest losses, while silicon-iron is better as far as losses are concerned. (Compare 1 mil. 4-79-Mo-Permalloy with 1 mil. silicon-iron, Fig. 6.)

From figure 6, it is easy to see that good powdered and ferrite cores have much smaller losses than laminated materials. Powdered core materials, sometimes designated as "Polyirons", have long been known. They consist of powdered pure iron, alloys, and organic binders, or of powdered ferromagnetic oxides.

Problems of powdered iron core development are: (a), to produce uniformly fine powders; (b), to insulate the metal particles from each other; and (c), to make the proportion of metal high in relation to the binder in order to obtain a relatively high permeability. These problems illustrate that compromises have to be made and that there are optimum compositions for individual frequency ranges. Low losses at rising frequency can only be maintained by decreasing the permeability. Because of the many series gaps in powdered material, permeabilities are inherently small and almost constant up to saturation. Permeabilities of commercial powdered core materials range loosely from 3 to 100. The effective permeability is still smaller in applications where the magnetic circuit is not closed.

It should be noted that loss data of commercial powdered cores are usually given as Q values of specific coils with specific cores. Such data are not suitable for material comparison on a universal basis.

Several powdered materials (shown by dotted lines in figures 6 and 7) have the lowest losses according to figure 6. This result is not very significant. The low losses of powdered cores are due mainly to their magnetic "dilution", that is, to the existence of a great number of small gaps between the ferromagnetic particles. These gaps also account for the low permeability of

powdered cores. Thus, the low losses of powdered cores are obtained at the expense of permeability. Actually, the best core material, with regard to losses, would be air or free space -- in other words, no magnetic material at all. If size is of no concern, it is known that low inductor losses can be obtained without cores. This illustrates the limited significance of loss data alone and the necessity for including the permeability in a comparison.

The introduction of an air gap in laminated or ferrite cores will also reduce losses and make these materials competitive. Q factors of approximately 600 have been reported on inductors which utilize ferrite pot cores with air gaps (see Ref. 18, p. 262). According to Snoek (Ref. 3), the loss reduction of ferrite cores, because of an air gap, is proportional to the reduction of permeability. This relationship can be expressed by the simple ratio:

$$\frac{D_m}{\mu} = \frac{D_{m'}}{\mu'} \quad (3)$$

where  $D_m$  and  $\mu$  refer to a closed ring core, while  $D_{m'}$  and  $\mu'$  refer to the same properties of a core with air gap. In addition to reducing losses, an air gap also reduces the effect of temperature on permeability.

The term  $\frac{D_m}{\mu}$  appears suitable for use as a general rating because: (a), it combines the most important core characteristics as D and  $\mu$ ; (b), it extends the applicability of the rating to ferrite cores with air gap; and (c), it can be computed easily from individual loss coefficients as defined by Legg (Ref. 12).

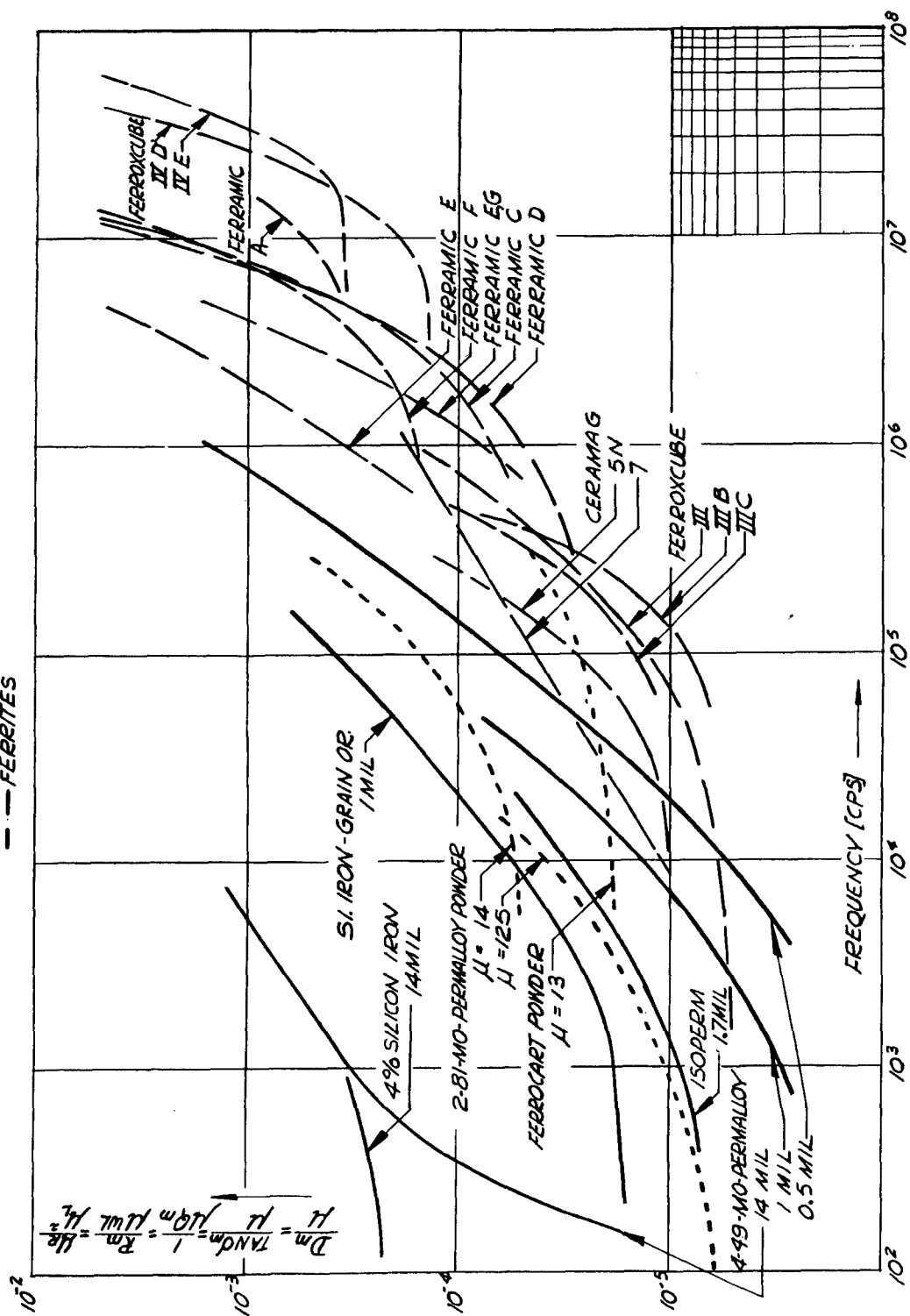
Figure 7 depicts  $\frac{D_m}{\mu}$  values versus frequency. Although the number of materials had to be limited, the following conclusions and ratings appear justified: powdered cores, which were superior in figure 6, are surpassed by laminated and ferrite cores; laminated cores rate better up to more than 10,000 cps from which frequency ferrites appear to be better. The unique position of Isoperm in figure 6 has been lost, and, in figure 7, Isoperm rates with other laminated materials. Ferrites which are often considered to fill a gap between laminated and powdered materials are found to be superior over powdered materials. Therefore, it may be expected that ferrites will come into wider use for high frequency applications. At present, the bulk of ferrite applications are in television receivers.

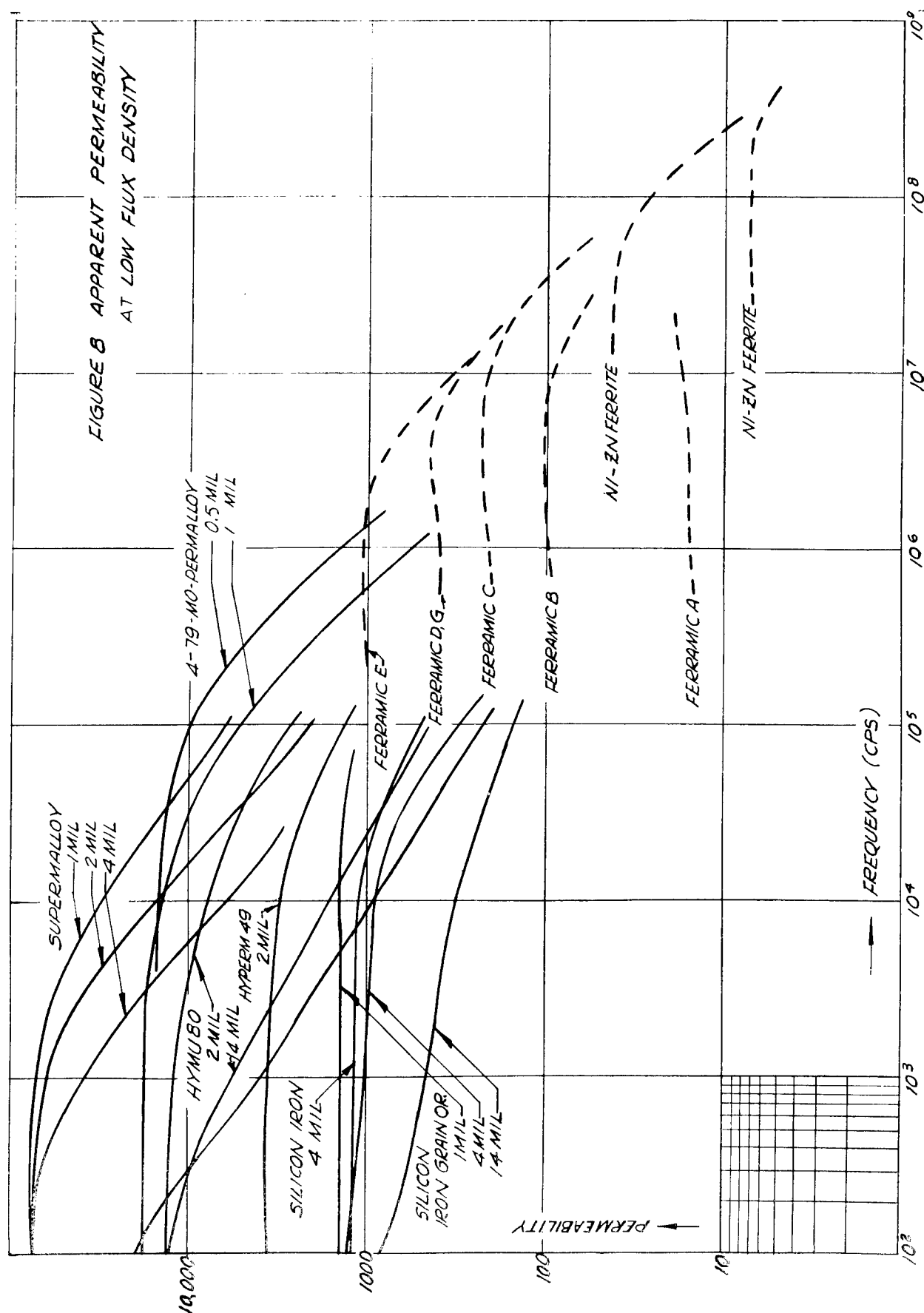
There are various other factors which cannot be incorporated in a universal rating but which may determine the selection of a material. Laminated cores, for example, are strain sensitive and often available as closed toroids only. Ferrites and powdered cores are relatively insensitive, substantially less in weight than laminated materials, and can be formed into a large variety of core shapes. The maximum operating temperatures of ferrite and powdered cores are, as a rule, lower than the maximum operating temperatures of laminated materials.

A less comprehensive but rather interesting diagram is obtained if the permeabilities of materials are plotted versus frequency, as in figure 8.

FIGURE 7 AC CHARACTERISTICS AT LOW FLUX DENSITY

LEGEND: — LAMINATED MATERIALS  
 --- POWDERED MATERIALS  
 - - - FERRITES





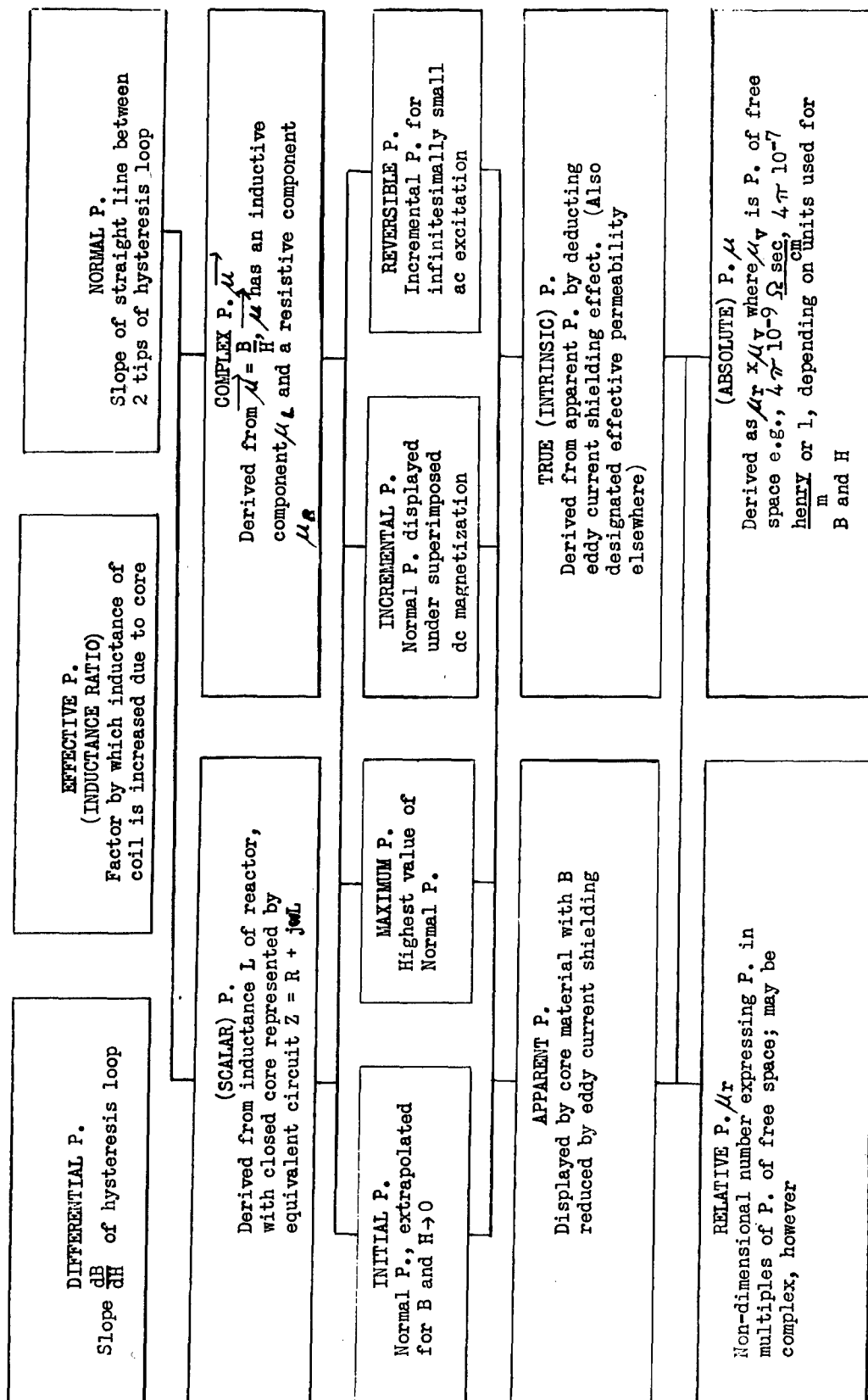


TABLE III Permeability Definitions Pertinent to Cyclic or Alternating Magnetization

Permeabilities are given for the low flux densities (as discussed in relation to figure 6) and can be termed initial permeabilities unless a more rigid definition (see Table III) excludes several of the data in figure 8.

The apparent permeability (see Table III) of a toroidal metallic core decreases with frequency because the eddy current shielding results in a lower flux density in the inner portions of a ferromagnetic lamination. This well-founded explanation is also substantiated in figure 8 where the permeabilities of thicker laminations decline faster at rising frequency. As in figures 6 and 7, figure 8 shows that the materials with better dc or low-frequency characteristics are surpassed at higher frequencies. Note that 2 mil. Hymu 80 surpasses the initial permeability of 2 mil. Supermalloy at approximately 40,000 cps although the resistivity of Supermalloy is slightly higher.

Lamination thickness and resistivity are the principal factors governing the reduction of the "apparent" permeability of laminated metallic cores over frequency. The "true or intrinsic" permeability of laminated metallic cores can be derived from the apparent permeabilities by calculating and eliminating the eddy current effect in the materials. This means that the true or intrinsic permeability could be realized and measured if the eddy current shielding effect could be avoided as is the case in some ferrites. The true or intrinsic permeability is of great interest for the study of both the ferromagnetic substances at microwave frequencies (see Ref. 2) and the phenomena which reduce the relative permeability to unity. The true permeabilities of metals are rather constant up to approximately  $10^8$  cps and reduce to unity in the region from  $10^{10}$  to  $10^{11}$  cps.

From the standpoint of core-material utilization, the apparent permeability, as plotted in figure 8, is of main concern because it represents the permeability which can be utilized in a core. Extrapolation of figure 8 indicates that the apparent permeabilities become unity in the region slightly above  $10^9$  cps.

Another interesting result of figure 8 is the fact that the highest apparent permeabilities of all available materials, as plotted over frequency, can be represented by a rather smooth envelope even though both laminated materials and ferrites are represented. The transition between both types of materials occurs at approximately 2 mc and is actually smoother than shown, taking into consideration that materials which are thinner than 0.5 mil. are available.

The practical significance of the envelope in figure 8 can be interpreted as a line which limits the highest initial permeabilities that can be obtained with the best magnetic cores at any given frequency.

Thus far in this report, the term "permeability" is understood to determine the impedance  $Z_m$  of a toroidal core which under simplifying assumptions reads:

$$Z_m = R_m + j\omega L = R_m + j\omega \frac{\mu N^2 A}{l} \quad (4)$$

If, however, the permeability is to be derived according to the definition

$$\mu = \frac{B}{H} \quad (5)$$



a discrepancy appears. While B is in quadrature with the applied voltage according to  $E_L = \frac{N d(AB)}{dt}$ , the magnetizing force is not in quadrature be-

cause H, according to definition, is proportional to the current which has a loss or in-phase component. Equation (5) can be applied to ac magnetization only if a phase angle is attributed to the permeability, that is, if the permeability is treated as a complex magnitude. In complex notation, the permeability has been given the form:

$$\vec{\mu} = \mu_L - j\mu_R \quad (6)$$

where  $\mu_L$  is an inductive component which so far has been referred to simply as permeability, and  $\mu_R$  is a resistive component. With this complex permeability,

$\vec{\mu}$  equation (4) has to be written simply as follows:

$$Z_m = j\omega \frac{\vec{\mu} N^2 A}{l} \quad (7)$$

Obviously, the notation of a complex permeability does not describe a new phenomenon in core materials. The usage of this notation is practical, not only because it allows the formal use of equation (5), but because it comprises all of the core characteristics represented in figures 6, 7, and 8. From equations (4) and (7) follows:

$$\vec{\mu} = \frac{R_m + j\omega L_m}{j\omega N^2 \frac{A}{l}} = \frac{L_m}{N^2 \frac{A}{l}} - j \frac{R_m}{\omega N^2 \frac{A}{l}} \quad (8)$$

Equating (8) with equation (6) gives:

$$\vec{\mu} = \mu_L - j\mu_R = \frac{L_m}{N^2 \frac{A}{l}} - j \frac{R_m}{\omega N^2 \frac{A}{l}} \quad (9)$$

This result serves to illustrate the components  $\mu_L$  and  $\mu_R$  which read:

$$\mu_L = \frac{L_m}{N^2 \frac{A}{l}} \quad (10)$$

and

$$\mu_R = \frac{R_m}{\omega N^2 \frac{A}{l}} \quad (11)$$

In figure 8,  $\mu_c$  is represented.

The dissipation factor  $D = \frac{R_m}{\omega L_m}$  derives from (10) and (11) as:

$$\frac{R_m}{\omega L_m} = \frac{\mu_r}{\mu_c} \quad (12)$$

The characteristics of figure 7 derive from equation (12) as  $\frac{R_m}{\omega L} = \frac{\mu_r}{\mu_c^2}$

because  $\mu$ , in conventional usage, is identical with  $\mu_c$  in vector notation.

The complex permeability lends itself well to illustrate the figure of merit  $\frac{\mu_r}{\mu_c^2}$  as plotted in figure 7. Again, as in figure 5, loci can be derived representing equal  $\frac{\mu_r}{\mu_c^2}$  values. The equation  $\frac{\mu_r}{\mu_c^2} = \text{Constant}$  yields parabolas as shown in figure 9. This diagram reveals the limitations of the factor  $\frac{\mu_r}{\mu_c^2}$  for material evaluation. Again, as with figure 5, the question, "Which materials are rated equal", can be answered. Materials with loss angles of higher than  $45^\circ$  should be excluded because  $\mu_r$  increases at a higher rate than  $\mu_c$ . Loss angles  $\delta$  of  $45^\circ$  or higher do not occur in practical core materials, and it can be concluded that the factor  $\frac{D_m}{\mu} = \frac{\mu_r}{\mu_c^2}$ , as plotted in figure 7, gives a satisfactory general rating of core materials.

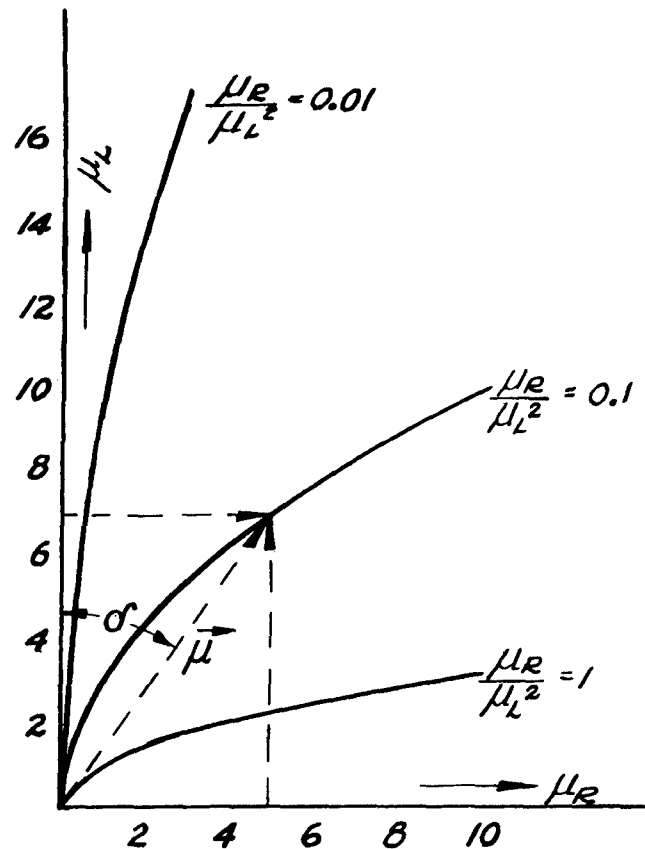


Fig. 9 Loci of Complex Permeability Vectors With Equal Figure of Merit  $\frac{\mu_R}{\mu_L^2}$

#### SUMMARY

The problem of evaluating and selecting magnetic core materials can be partially solved by using suitable figures of merit for characterizing materials. Such figures of merit are exciting plus in-phase volt-amperes and dissipation factor over permeability. Material evaluations, which are based on these characteristics, show the advantages of ferrites over laminated and powdered materials, particularly, at high frequencies. The use of the complex permeability concept for describing the characteristics of materials appears advantageous.

### INDEX OF SYMBOLS

$A$	Sectional area of core
$B$	Flux density in core
$\cos \phi$	Power factor
$D$	Dissipation factor
$E$	Voltage
$\phi$	Loss angle (see figure 9)
$H$	Magnetizing force
$j$	Rotative operator
$L$	Inductance
$l$	Mean length of toroidal core
$\mu$	Permeability (see also Table III)
$N$	Number of turns on core
$\omega$	Circular frequency
$Q$	Quality or storage factor
$R$	Resistance
$\tan \phi$	Loss tangent
$Z$	Impedance

### Subscripts

$c$	Refers to coil
$L$	Denotes inductive component
$m$	Refers to magnetic core
$R$	Denotes resistive component
$r$	Denotes relative component
$s$	Denotes equivalent series component
$v$	Denotes vacuum component

## BIBLIOGRAPHY

1. Bozorth, R. M. Ferromagnetism. Van Nostrand Co., New York, New York. 1951.
2. Rado, G. T. Ferromagnetic Phenomena At Microwave Frequencies. Advances In Electronics II. Academic Press Inc., New York, New York. 1950. pp. 251-296
3. Snoek, J. L. New Developments In Ferromagnetic Materials. Elsevier Publishing Co., Houston, Texas. 1947
4. Boothby, O. L., Bozorth, R. M. A New Magnetic Material of High Permeability. J. Appl. Phys. V.18. 1947. pp. 173-176.
5. Brockman, F. G. Magnetic Ferrites for High Frequency Uses. Elec. Eng. V.68. December 1949. pp. 1077-1080.
6. Chegwiddden, R. A.. A Review of Magnetic Materials Especially for Communication Systems. Metal Progress. V.54. November 1948. pp. 705-714.
7. Crede, J. H., Martin, J. P. Magnetic Characteristics of an Oriented 50 percent Nickel Iron Alloy. J. Appl. Phys. V.20. 1949. pp. 966-971.
8. Dillinger, J. F., Bozorth, R. M. Physics. V.6. 1935. pp. 279-291.
9. Elmen, G. W. Magnetic Alloys of Iron, Nickel and Cobalt. Elec. Eng. V. 54. 1935. pp. 1292-1299.
10. Ganz, A. G. Applications of Thin Permalloy Tape in Wide Band Telephone and Pulse Transformers. Elec. Eng. Transactions. V.65. 1946. pp. 177-183
11. Legg, V. E. Survey of Magnetic Materials and Applications in the Telephone System. Bell System Tech. J. V. XVIII. 1939. pp. 438-464.
12. Legg, V. E. Magnetic Measurements at Low Flux Densities Using the Alternating Current Bridge. Bell System Tech. J. V. XV. 1936. pp. 39-62.
13. Legg, V. E., Given, F. J. Compressed Powdered Molybdenum Permalloy. Bell System Tech. J. V. 19. July 1940. pp. 385-406.
14. Macfadyen, K. W. Vector Permeability. J. Inst. Elec. Engrs. V.94. 1947. P. III, pp. 407-414.
15. Magnetic Engineering Practice. Distributed by Magnetic Metals Co., Camden, New Jersey.
16. Properties of Deltamax, 4-79-Mo-Permalloy, Supermalloy. Bulletin TC-100 by The Arnold Engineering Co., Marengo, Illinois.
17. Snyder, C. L., Albers-Schoenberg, E., Goldsmith, H.A. Magnetic Ferrites. Electrical Manufacturing. V. 44. December 1949. pp. 86-91.

18. Symposium on Ferromagnetic Materials. Proc. Inst. Elec. Engrs. V. 97.  
1950. Part II, pp. 119-272.
19. Went, J. J., Gorter, E. E. The Magnetic and Electrical Properties of  
Ferroxcube Materials. Phillips Tech. Rev. V. 13. January 1952.  
pp. 181-193.

# DISTRIBUTION LIST

<u>Cys</u>	<u>ACTIVITIES AT WRIGHT-PATTERSON AIR FORCE BASE</u>	<u>Cys</u>	<u>ACTIVITIES AT WRIGHT-PATTERSON AIR FORCE BASE (Cont'd)</u>
2	ASTIA-DSC-SA	1	WCLGD Attn: Dr. R. M. Wundt
1	ATIA	1	WCLGO Attn: R. J. Nordland
1	MCLI Attn: J. J. D'Azzo	1	WCLGS Attn: Lt. Col. W. Hilt
2	WCAPP	1	WCLND Attn: Capt. A. D. Clark
1	WCLB	1	WCLNO
6	WCLBS	1	WCLNO1 Attn: A. R. Knight
35	WCLCO2	1	WCLNO3 Attn: K. D. Bailey
1	WCLE Attn: Mr. Harding	1	WCLPG2
1	WCLLE Attn: R. O. McCants	3	WCLRO5
2	WCLEI Attn: John H. Kearns Arthur L. Martinson	1	WCLSO
2	WCLEM3 Attn: G. T. Berry Capt. A. L. Ingelfinger	1	WCRDB Attn: M. A. McLennan
2	WCLEQ2 Attn: J. T. Cassidy H. Erdman	2	WCOWP (For Rand Corp., Attn: The Library, 1500 Fourth St., Santa Monica, Calif.)
3	WCLEQ5 Attn: V. O. Day, Jr. L. G. Green Maj. B. K. Slonneger	1	WCRRN Attn: Capt. R. E. Sellers
1	WCLEH5 Attn: Capt. H. P. Scheuerman	2	WCRTL Attn: Dr. H. Adenstedt
1	WCLF	1	WCRT0
1	WCLFE		
1	WCLGA2		

# DISTRIBUTION LIST (Cont'd)

## Cys      OTHER DEPARTMENTS OF DEFENSE

### Air Force

Commanding General  
Air Force Cambridge Research  
Center  
1 Attn: Mr. W. G. Field  
1 Attn: Electronics Research  
Library, CRRSA-1  
230 Albany Street  
Cambridge 39, Massachusetts  
  
1 Commanding General  
Air Research and Development  
Command  
Attn: Mr. Charles Yost  
P. O. Box 1395  
Baltimore 3, Maryland  
  
Commanding General  
Rome Air Development Center  
1 Attn: Research Library,  
RCRES2  
1 Attn: J. L. Briggs, RCRTG-5  
Griffiss Air Force Base  
Rome, New York  
  
1 Air Force Development Field  
Representative  
Signal Corps Engineering  
Laboratories  
Fort Monmouth, New Jersey  
  
1 Air Force Engineering Field  
Representative  
Code 1110, Naval Research  
Laboratory  
Washington 25, D. C.  
  
1 Air University Library  
Attn: CR4229  
Maxwell Air Force Base  
Alabama

## Cys      OTHER DEPARTMENTS OF DEFENSE (Cont'd)

### Army

1 Office of the Chief of  
Ordnance  
Attn: ORDTB-Materials-NM  
Washington 25, D. C.  
  
1 Commanding Officer  
Redstone Arsenal  
Attn: ORDDW-TMPE  
Ordnance Corps  
Huntsville, Alabama  
  
1 Commanding General  
Signal Corps Engineering  
Laboratories  
Attn: Technical Reports  
Library  
Fort Monmouth, New Jersey  
  
1 Office of the Chief Signal  
Officer  
SIGTA-2S  
Engineering Technical Division  
Washington 25, D. C.

### Navy

1 Commander Naval Ordnance  
Laboratory  
Attn: Mr. H. H. Woodson, W.B.  
Building 24  
Silver Spring, Maryland  
  
2 Chief, Bureau of Aeronautics  
Attn: Technical Data Division  
TD-41  
Navy Department  
Washington 25, D. C.  
  
1 Chief of Naval Research  
Attn: Technical Information  
Division  
Library of Congress  
Washington 25, D. C.



# DISTRIBUTION LIST (Cont'd)

## Cys Navy (Cont'd)

- 1 Chief, Bureau of Aeronautics  
Attn: Electronics Division,  
Material Coordination  
Section
- 1 Attn: Mr. H. R. Thoman,  
Code EL-412  
Navy Department  
Washington 25, D. C.
- 1 Chief, Bureau of Ships  
Attn: Code 930A
- 1 Attn: Mr. J. Hall, Code 817
- 1 Attn: Code 934A
- 1 Attn: Mr. J. W. Brush, Code 818C
- 1 Attn: Mr. R. T. Williams,  
Code 336 J. O.  
Navy Department  
Washington 25, D. C.
- 1 U. S. Navy Electronics Library  
Attn: Mr. A. H. Attebury  
Code 733  
San Diego 52, California
- 1 Office of the Chief of Ordnance  
Attn: Mr. L. Schlisinger  
Navy Department  
Washington 25, D. C.

## OTHER U. S. GOVERNMENT AGENCIES

- 1 National Bureau of Standards  
High Frequency Measurements  
Attn: Mr. Haas  
Washington 25, D. C.
- 1 National Bureau of Standards  
Magnetics  
Attn: Mr. Sanford  
Washington, D. C.
- 1 National Bureau of Standards  
Div. 12  
Miniaturization Laboratory  
Attn: Mr. Gustave Shapiro  
Washington 25, D. C.

## Cys OTHER U. S. GOVERNMENT AGENCIES (Cont'd)

- 1 Department of Commerce  
Office of Technical Services  
Attn: Library  
Washington 25, D. C.

## MISCELLANEOUS

- 2 Allegheny-Ludlum Steel Corp.  
Brackenridge, Pennsylvania
- 2 Armco Steel Corporation  
Research Laboratories  
Attn: Mr. G. H. Cole  
Middletown, Ohio
- 2 Arnold Engineering Company  
Marengo, Illinois
- 1 Beech Aircraft Corporation  
Attn: Chief Engineer  
6600 E. Central Avenue  
Wichita 1, Kansas
- 1 Bell Aircraft Corporation  
Attn: Mr. J. D. Shantz  
Niagara Falls, New York
- 2 Bell Telephone Laboratories  
Murray Hill  
New Jersey
- 1 Bendix Aviation Corporation  
Bendix Radio Division  
Attn: Dr. Kenneth F. Umpleby  
Towson 4, Maryland
- 1 Bendix Aviation Corporation  
Bendix Radio Division  
Attn: Mr. Norman Raymond  
Baltimore 4, Maryland
- 1 Boeing Airplane Company  
Bomarc Project  
George M. Adams (Attn:  
Richard Poppe)  
Seattle, Washington

# DISTRIBUTION LIST (Cont'd)

<u>Cys</u>	<u>MISCELLANEOUS (Cont'd)</u>	<u>Cys</u>	<u>MISCELLANEOUS (Cont'd)</u>
1	Boeing Airplane Company Physical Research Unit Attn: Robert W. Illman Seattle, Washington	1	Consolidated-Vultee Aircraft Corp. Attn: Chief Engineer Fort Worth 1, Texas
1	Boeing Airplane Company Seattle Division Attn: G. Hollingsworth Seattle 14, Washington	1	Cook Research Laboratories 1457 Diversey Parkway Chicago 14, Illinois
1	Boeing Airplane Company Wichita Division Attn: Chief Engineer Wichita 1, Kansas	1	Crosley Corporation Attn: Mr. Felix 1325 Arlington Avenue Cincinnati, Ohio
1	Burroughs Adding Machine Co. Attn: Mr. I. L. Auerbach 511 N. Broad Street Philadelphia 23, Pennsylvania	1	Douglas Aircraft Company, Inc. Attn: Mr. H. M. Sheffield 3855 Lakewood Boulevard Long Beach, California
1	Chase Aircraft Co., Inc. Attn: Chief Engineer DeCot and Parkaway Avenues Hangar Building 34 Mercer County Airport West Trenton, New Jersey	1	Douglas Aircraft Company, Inc. Attn: Mr. E. F. Burton, Chief Engineer 3000 Ocean Park Boulevard Santa Monica, California
1	Consolidated-Vultee Aircraft Corp. Bureau of Aeronautics Repre- sentative For processing to Ryan Aeronautical Co. San Diego 12, California	1	Douglas Aircraft Company, Inc. Attn: Mr. E. H. Heinemann, Chief Engineer 827 Lapham Street El Segundo, California
1	Consolidated-Vultee Aircraft Corp. Electronics and Guidance Section Attn: W. J. Zable Thru: AF Plant Representative Western Air Procurement District P. O. Box 1950, 3156 Pacific Highway San Diego 12, California	1	Ford Instrument Company 3110 Thomson Avenue Long Island City 1, New York
2	Consolidated-Vultee Aircraft Corp. Attn: Dr. W. J. Short San Diego Division San Diego, California	2	Ferroxcube Corporation of America Attn: Mr. W. W. Stifler Saugerties, New York
		2	General Ceramics and Steatite Corporation Attn: Mr. C. L. Snyder Keasbey, New Jersey
		1	General Electric Company Electronics Division Syracuse, New York

# DISTRIBUTION LIST (Cont'd)

## Cys MISCELLANEOUS (Cont'd)

1 Goodyear Aircraft Company  
Attn: Dept. 29C, J. F.  
Redmond  
Akron 15, Ohio

3 Grumman Aircraft Engineering  
Corp.  
Attn: Chief Engineer  
Bethpage, L. I., New York

1 Hughes Aircraft Company  
Attn: Morris Weinberg  
AET - Department O4  
Florence and Teale Streets  
Culver City, California

3 Hughes Aircraft Company  
Research & Development Labs.  
Attn: Dr. L. C. Van Atta  
Culver City, California

1 Hughes Aircraft Company  
Attn: George Beck, Dept. 29  
Florence and Teale Streets  
Culver City, California

1 Hughes Aircraft Company  
Culver City, California

1 International Business Machines  
590 Madison Avenue  
New York 22, New York

1 Lear, Inc.  
110 Ionia Avenue, N. W.  
Grand Rapids, Michigan

1 Lockheed Aircraft Corp.  
Attn: Mr. W. R. Martin  
Burbank, California

1 Lockheed Aircraft Company  
Factory A, Dept. 7225  
Attn: P. A. Beck  
P. O. Box 71  
Burbank, California

## Cys MISCELLANEOUS (Cont'd)

1 Magnetic Metals Company  
Camden, New Jersey

1 Magnetic Research Corporation  
Attn: Mr. H. H. Woerdmann  
318 Kansas Street  
El Segundo, California

1 P. R. Mallory and Company  
Indianapolis, Indiana

1 Minneapolis-Honeywell Regulator  
Company  
2747 Fourth and South Sts.  
Attn: Mr. A. P. Upton  
Minneapolis, Minn.

1 McDonnell Aircraft Corporation  
Attn: Engineering Library  
P. O. Box 516  
Lambert Municipal Airport  
St. Louis 21, Missouri

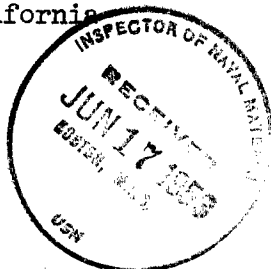
1 North American Aviation, Inc.  
Attn: Dr. Ashby  
Downey, California

1 North American Aviation, Inc.  
Standards Engineering Group  
Attn: Mr. E. F. Hagar  
12214 Lakewood Blvd.  
Downey, California

1 North American Aviation, Inc.  
Attn: Mr. L. L. Waite  
Downey, California

2 North American Aviation, Inc.  
Attn: Mr. Dave Mason  
Engineering Data Section  
Los Angeles International  
Airport  
Los Angeles 45, California

1 North American Aviation, Inc.  
Aerophysics Laboratory  
Attn: Dr. J. A. Marsh  
Downey, California



# DISTRIBUTION LIST (Cont'd)

## Cys      MISCELLANEOUS (Cont'd)

- 1      North American Aviation, Inc.  
Aerophysics Laboratory  
Attn: Library  
12214 Lakewood Blvd.  
Downey, California
- 1      Northrop Aircraft Incorporated  
Attn: Northrop Library, For  
      MX-755  
Hawthorne, California
- 2      Northrop Aircraft Incorporated  
Attn: Northrop Library  
      Department 2135  
Hawthorne, California
- 3      Northrop Aircraft Incorporated  
Attn: Chief Mechanical Design  
Hawthorne, California
- 1      Radio Corporation of America  
Attn: Mr. D. H. Cunningham  
      Parts Engineering  
Front and Cooper Street  
Camden 1, New Jersey
- 1      Radio Corporation of America  
Victor Division  
Engineering Products Dept.  
Attn: F. C. Collings  
Camden, New Jersey
- 1      Republic Aviation Corp.  
Attn: Engineering Library  
Farmingdale, New York
- 1      Sperry Gyroscope Company  
Great Neck, Long Island, N.Y.
- 1      Sprague Electric Company  
North Adams  
Massachusetts
- 2      Stackpole Carbon Company  
St. Marys  
Pennsylvania

## Cys      MISCELLANEOUS (Cont'd)

- 1      Stanford Research Institute  
Attn: Mr. H. W. Smith  
Stanford, California
- 2      D. M. Steward Mfg. Company  
Attn: W. S. Mills  
Chattanooga, Tennessee
- 1      United Aircraft Corporation  
Pratt & Whitney Aircraft Div.  
Attn: G. E. Beardsley  
362 South Main Street  
East Hartford 8, Conn.
- 1      United Aircraft Corporation  
Chance-Vought Aircraft Div.  
Attn: Chief Engineer  
Dallas, Texas
- 2      Westinghouse Electric Corp.  
East Pittsburgh, Pennsylvania
- 1      Westinghouse Electric Corp.  
Specialty Transformer Dept.  
Attn: Mr. T. F. Saffold  
Sharon, Pennsylvania